

Mercury Control with Calcium-Based Sorbents and Oxidizing Agents

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Abstract

Sorbent development work in the state-of-the-art catalyst test facility at SRI is underway to find optimized compositions of calcium and carbon for mercury removal. Designer sorbents are sought that will allow the sorbent composition to meet the catalytic and sorbent needs of a particular coal type, power-plant configuration, and boiler operation. For example, a utility that produces a high-calcium, low-UBC flyash will need a different composition than a plant that produces a high-UBC, low-calcium flyash. Once an optimum calcium-based sorbent has been identified, it will be tested in the Combustion Research Facility at Southern Research Institute, for its effectiveness at mercury removal across an ESP and a Baghouse.

This quarter, activated carbon, carbon black, hydrated lime, and several designer Ca-carbon sorbents were compared to each other in terms of mercury removal effectiveness in the catalyst test facility (CTF) at SRI. This comparison was made by testing each sorbent across a temperature range from 300 °F to 1100 °F, changing the temperature by 200 °F every hour. It was shown that carbon black behaved somewhat similar to NORIT America Inc. FGD activated carbon, with a little less capture for the same mass, but costing 1/3 that of the activated carbon. Consistent with previous pilot-scale tests, hydrated lime alone was not an effective mercury sorbent. However, calcium-based carbon-impregnated sorbents were effective at capturing mercury at 300 °F and 500 °F, and were also effective at capturing mercury at 700 °F, unlike the purely-carbon sorbents.

Future tests are underway to fully exploit the synergistic relationship between calcium and carbon observed in these bench-scale and previous pilot-scale experiments.

Table of Contents

Section	Page
Introduction.....	1
Experimental	2
Results	6
Discussion	10
Conclusions	11
Future Work	11
References	11

List of Figures

Figure	Page
1 CTF quartz furnace with catalyst at ~1000 °C	3
2 CTF furnace, gas-injection system, flue-gas CEMs, and Hg gas-conditioning system.....	3
3 CTF gas flow system	4
4 Background	5
5 NORIT FGD Activated Carbon	7
6 Carbon Black (loose black)	7
7 Hydrated Lime	8
8 Calcium-based sorbent with 10% carbon bound	9
9 Calcium-based sorbent with 4% carbon bound	9
10 Comparison of sorbents for Hg-mitigation on an equal mass basis	10

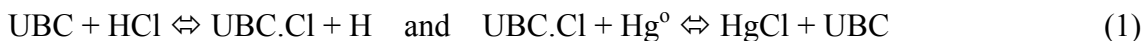
Introduction

The predominant forms of mercury in coal-fired flue gas are elemental (Hg^0) and oxidized (HgCl_2) [1-3]. The percentage of oxidized mercury in the stack effluent of a particular power plant depends on the coal type, combustion efficiency, and the pollution control equipment used. Essentially all of the mercury entering the furnace with the coal is vaporized and exists in the elemental form until the flue gases cool below $\sim 600^\circ\text{C}$ ($\sim 1000^\circ\text{F}$) [1-3]. The oxidation of mercury in coal-fired boiler systems is kinetically limited [1-3]. Because the concentration of mercury is very small in flue gas, any favorable mercury-oxidation reaction does not have the ability to promulgate itself. In virtually every conceivable competitive reaction, the competing gas component, much in excess of mercury, dominates. On the other hand, where the formation of mercuric compounds is thermodynamically favored, the kinetically controlled oxidation is generally slow unless the oxidant is in vast abundance compared with mercury.

In addition to the trace nature of mercury in coal-fired boilers, favorable reactions for mercury oxidation have short temperature/time windows. Consequently, the extent of mercury oxidation is highly dependent on catalytic processes. Heterogeneous catalysis enhances mercury oxidation reactions in two ways. First of all, disperse solid catalytic material provides sorption sites upon which reactions may take place. In addition, heterogeneous catalysis enhances mercury oxidation by effectively making available gas components (such as Cl) that are otherwise scavenged by competing gas species present at much higher concentrations.

A system of reactions, which include significant chlorine-speciation reactions, has been proposed to describe homogeneous Hg -oxidation [4]. This set of governing reactions allows direct oxidation of Hg^0 to HgCl and HgCl to HgCl_2 by the following four chlorine species with different reaction rates: Cl , Cl_2 , HCl , and HOCl [4]. This system of equations has been shown to effectively predict mercury speciation for specific homogeneous systems [2]. However, the homogeneous model alone consistently under predicts the oxidation of mercury from coal-fired boilers [5]. Hence, it was important to identify and describe the heterogeneous reactions that dominate the mercury-oxidation process.

It has been shown in previous work [6,7] that UBC is the dominant catalyst inherent in coal flyash, for Hg -oxidation enhancement. Niksa et. al. [8] suggested a possible mechanism whereby UBC can catalyze mercury oxidation, as follows:



The March03 and June03 Quarterly Reports show that it is indeed the UBC that is responsible for the observed higher levels of oxidized mercury found in bituminous coal flue gas compared with PRB (high-calcium and low-UBC) flue gas [6,9,10]. Considerable evidence has been presented showing that calcium is an effective sorbent for mercury, provided that sufficient UBC is present to help catalyze the capture. Data presented previously suggested that UBC was needed both to catalyze mercury oxidation and enhance mercury capture by calcium [6,7], and this observation was later firmly established through the means of dual baghouse tests described in the September03 Quarterly Report [11]. It was conclusively shown that UBC ($0.1\% < \text{UBC} < 5\%$) enhanced the capture of oxidized mercury by calcium in a pilot-scale baghouse as well as the capture of elemental mercury. Calcium sorbent was ineffective at capturing oxidized mercury without UBC present, similar to low-carbon PRB ash.

This synergistic relationship between UBC and calcium (either from PRB ash or from injected sorbents) has been observed during coal blending [9-12], but it has been shown to be much more pronounced for PRB-only tests, where the UBC content was increased via combustion modifications [6-7, 10-11].

One possible mechanism whereby UBC may enhance mercury capture by calcium is by providing a sorption site for mercury to attach through van der Waals' forces, thus slowing the mercury molecules down and bringing them in contact or near contact with adjacent calcium sites where reactions may take place. In fact, the reaction of elemental mercury with chlorinated carbon sites, i.e., UBC.Cl⁻ (see Equ. 1), followed by reaction with nearby calcium sites, may provide a semi-direct pathway for the capture of elemental mercury by calcium in baghouse filter cakes.

It is true that most (not all) of the UBC present in bituminous coal ash is in separate particles from the rest of the flyash [13], and in a filter cake, the carbon is not intimately associated with the calcium injected as a sorbent. Nevertheless, there may be a sufficient number of contact sites between carbon and calcium, to allow significant mercury capture enhancement to occur. Furthermore, PRB coal ash typically retains its relatively small percentage of UBC on the surface of high-calcium ash particles, thus making the prospects of a two-step (oxidation followed by capture in the case of Hg⁰ and sorption followed by capture in the case of HgCl₂) reaction even more likely. This is one of the main reasons why increasing UBC through combustion modifications with PRB only was more effective at removing mercury than coal blending.

Sorbent development has been pursued this quarter based on this understanding of general global mechanisms in real coal-fired flue gas and under conditions, including temperature/time histories, that are relevant to full-scale boiler systems. The state-of-the-art catalyst test facility (CTF) at Southern Research Institute has been adapted for mercury sorbent development. The CTF has been used to compare designer calcium-based sorbents with purely-carbon sorbents. Ultimately, optimized sorbents will be tested in the CRF for most effective mercury removal in a baghouse and/or ESP. Eventually, designer sorbents are sought that will have compositions specifically designed for each individual power station coal type, system, pollution control devices, and operating conditions.

Experimental

Figures 1 and 2 show pictures of the CTF's quartz furnace (micro-reactor), gas-conditioning bubblers for mercury speciation and stabilization prior to mercury monitoring, flue-gas continuous emission monitors (CEMs), and gas-flow control systems. Both elemental and total mercury are measured at the outlet of the CTF. The CTF simulates clean (no particles) flue gas with all the major flue-gas species present, including CO, CO₂, H₂O, O₂, N₂, HCl, NO, SO₂, SO₃, and Hg⁰, in concentrations that exist in the flue gases of existing power plants, burning specific coal types. The simulated flue gas is originated from compressed gas cylinders. The gases from the cylinders are then mixed to known concentrations by use of mass flow controllers. Evaporating liquid water generates the appropriate moisture content in the gas stream, and mercury is added to the system via a permeation device manufactured by Vici Metronics. The simulated flue-gas stream is well mixed and preheated before entering the reaction chamber. A 3"-diameter tube furnace heats the reaction chamber, and a 1½"-tubular reactor carries the gases through the furnace and holds the sorbent samples.

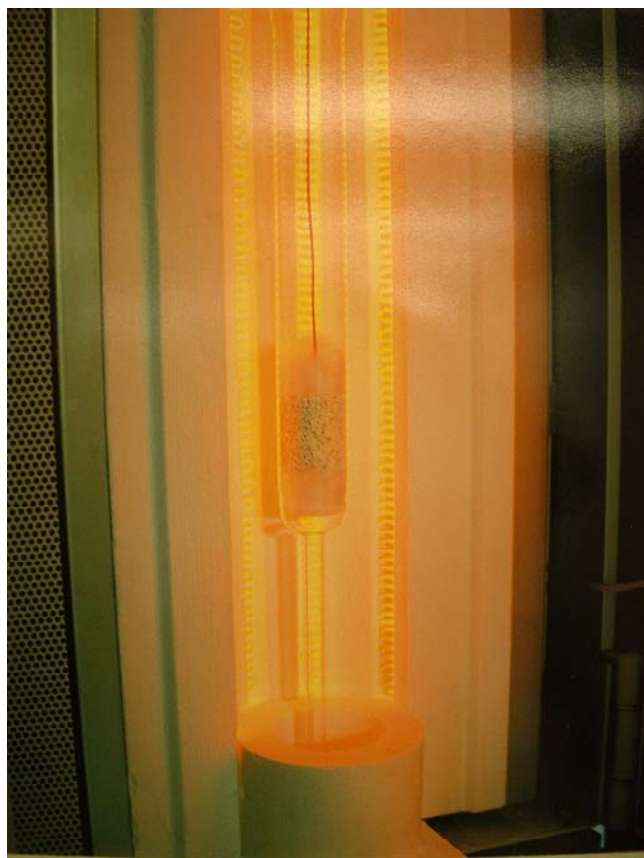


Figure 1. CTF quartz furnace with catalyst at $\sim 1000\text{ }^{\circ}\text{C}$.



Figure 2. CTF furnace, gas-injection system, flue-gas CEMs, and Hg gas-conditioning system.

All heated sections of the micro-reactor within the CTF system are made of quartz glass to limit side reactions that might occur as a result of wall effects. A semi-continuous emission monitor (SCEM) is employed to detect the mercury levels exiting the reaction chamber. A gas-conditioning system is used to convert all Hg into the elemental form, for detection using a combined gold-trap and atomic fluorescence monitor. A Tekran Model 2573A Mercury Vapor Analyzer is used to detect the elemental mercury. Along with mercury, simultaneous measurements of oxygen, carbon dioxide, nitrogen oxides, and sulfur dioxide are made using continuous emission monitors. Figure 3 shows a schematic of the CTF system layout.

Even the most rigorous of bench-scale experiments are not sufficient to mimic the full-scale conditions of a coal-fired power plant. Therefore, the CTF was and will continue only to be used for comparison with known effective mercury sorbents and for optimization prior to testing in the pilot-scale unit, where conditions are comparable to full-scale units.

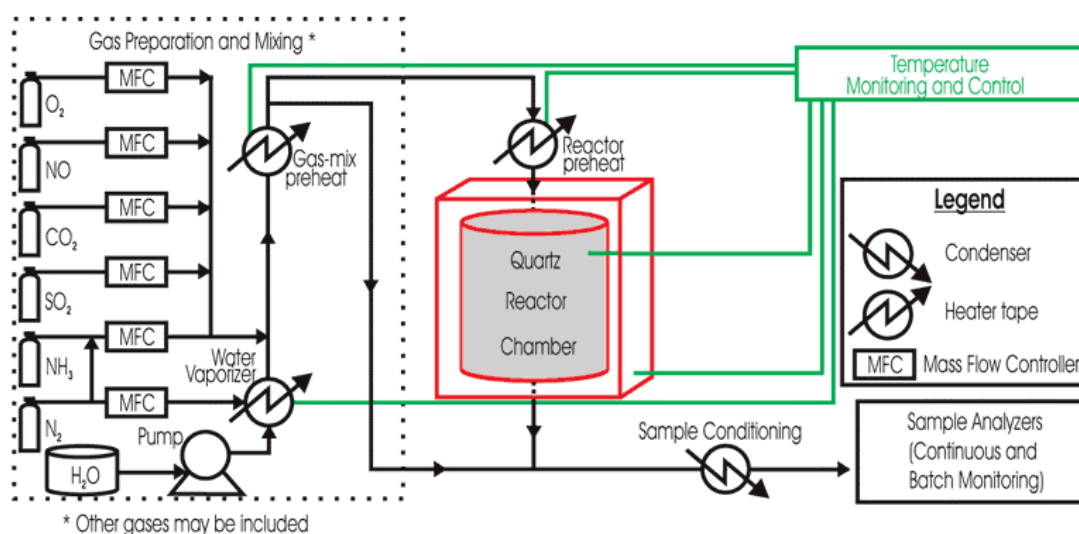


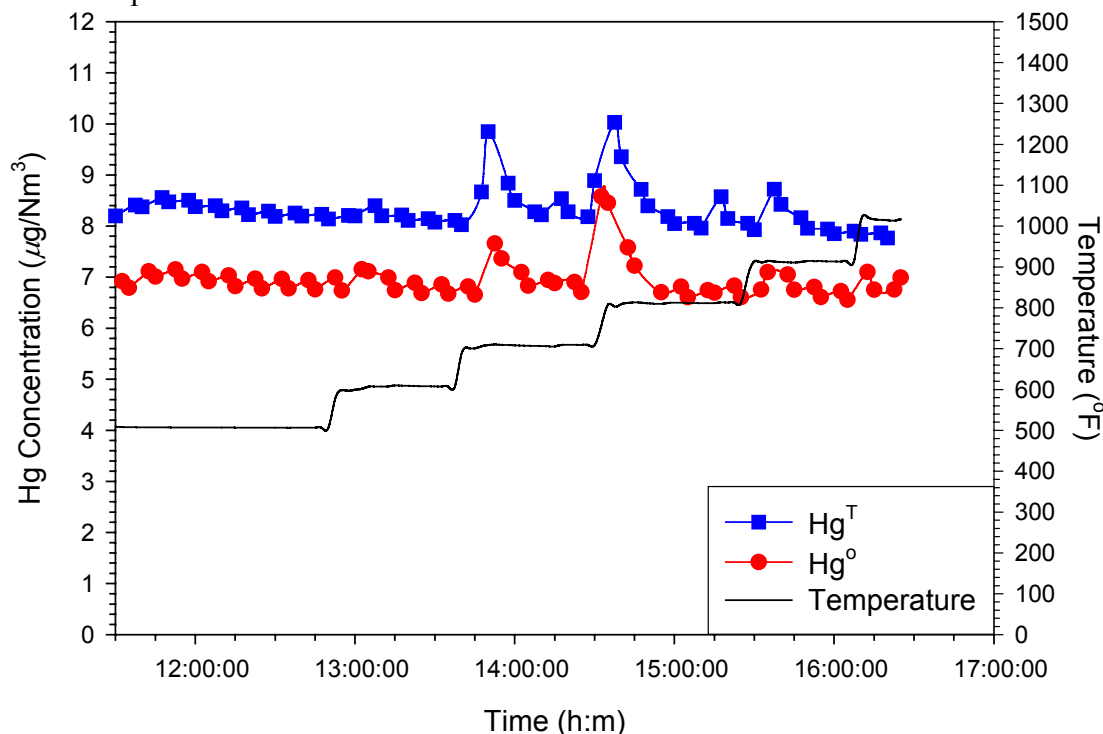
Figure 3. CTF gas flow system.

The CTF system (see Fig. 3) was characterized for proper mercury delivery and side reactions inherent in the system. The mercury delivery system used for these experiments was a permeation tube and device manufactured by Vici Metronics. This device emits a constant mass rate of mercury that is directly injected into the gas-flow stream. The delivery rate of mercury was confirmed by collecting the output by wet chemistry and detection by analytical testing. This was done directly from the output of the permeation device, thus eliminating any biasing from the rest of the system. Once the delivery rate was confirmed, the micro-reactor portion of the CTF system was characterized for side reactions. This was performed in two steps, first using an inert stream of nitrogen and then a simulated flue-gas stream. In each case, the source mercury stream was injected into the larger stream of gas in the micro-reactor, and recoveries were measured. During inert injection of $10 \mu\text{g}/\text{Nm}^3$ of mercury, a recovery of $10 \pm 0.5 \mu\text{g}/\text{Nm}^3$ of mercury was measured. Of the total mercury recovered, $>95\%$ was elemental mercury. During simulated flue-gas injection, the level of mercury recovered was also $10 \pm 0.5 \mu\text{g}/\text{Nm}^3$. However, of the total mercury recovered, the elemental mercury fraction was only $\sim 75\%$. The simulated flue-gas conditions are provided in Table 1. The total system flow rate for this gas was 5 lpm (dry) at 70 °F and 1 atm.

Table 1. Simulated flue-gas composition.

Simulated Flue Gas Concentrations	
<i>Gas Component</i>	<i>Concentration</i>
➤ Water Vapor	10 vol%
➤ Oxygen	6 vol % - Dry
➤ Carbon Dioxide	15 vol% - Dry
➤ Sulfur Dioxide	500 ppmv - Dry
➤ Hydrogen Chloride	2 ppmv - Dry
➤ Nitrogen Oxide	300 ppmv -Dry
➤ Mercury	10 $\mu\text{g}/\text{m}^3$ - Dry
➤ Nitrogen	Balance - Dry
Total	100 vol% Dry

In addition to the above characterization and validation of the CTF system, a background mercury baseline was performed for the temperature range across which the sorbent-comparison experiments were to be performed. A blank reactor (containing no sorbent) was inserted into the furnace. The flow rates and gas composition were set to those shown in Table 1. Six different temperatures were consecutively examined, specifically 500 °F, 600 °F, 700 °F, 800 °F, 900 °F, and 1000 °F (see Fig. 4). As shown in Fig. 4, the total and elemental mercury steady-state concentrations in the simulated flue gas were unaffected by temperature. An initial spike of mercury was observed each time the temperature was increased, but this transition quickly (<10 minutes) returned to a steady-state level similar to previous steady-state conditions obtained at lower temperatures.

**Figure 4.** Background.

The flow rates, temperatures, and concentrations were continuously monitored and maintained throughout the test program. Three-gram samples of each sorbent were used during

each individual experiment. These samples were put into the quartz reactor with a quartz frit and quartz filter paper to prevent the sample from contaminating the gas-flow system. The bed depth of the sorbents was approximately one-third of an inch in the direction of gas flow. At the beginning of each experiment, a blank quartz reactor was inserted into the gas stream to collect baseline data. After sufficient data were collected, the blank reactor was removed and immediately replaced with the sorbent-packed reactor. The reactor was allowed to come to the initial 300 °F temperature at which time the exposure experiment began. The sorbent was exposed to simulated flue gas for one hour at 300 °F, after which the temperature was increased to 500 °F for another hour, then to 700 °F and so on until reaching 1100 °F. The temperature was then decreased, repeating the temperature conditions in a descending fashion until reaching the initial 300 °F set point. At the conclusion of each experiment, the quartz filter paper and exposed sample were disposed of and the quartz reaction chamber was thoroughly cleaned and repacked with the next sorbent to be tested. These steps were precisely repeated for each sorbent, in order to allow a relative comparison of Hg-removal effectiveness.

Table 2 contains a list of sorbents tested this quarter along with a description of the sorbent and its internal surface area. As previously stated, 3-grams of each sorbent were used for each test. Surface area was considered to be an inherent property of each sorbent.

Table 2. Sorbent Characteristics.

Sorbent Type	Sorbent Description	S. Area (m ² /g)	Ave Part. size (ave)
Activated Carbon	NORIT Americas Inc. DARCO FGD Activated Carbon. This is a lignite coal-based activated carbon.	600	90% < 45 μm
Carbon Black	Continental Carbon 200 Series loose black, Carbon Black. 1.5 μm particles agglomerated from ~30-0.15 μm smoke.	120	1.5 μm
Hydrated Lime	Dravo hydrated lime from Longview Plant in Saginaw.	~18	>10 μm
CaSorb + 10% C	Lime with 10% bound Activated Carbon (listed above).	76	>10 μm
CaSorb + 4% C	Lime with 4% bound Activated Carbon (listed above).	27	>10 μm

Results

The results from applying the test procedure described above for each of the individual sorbent types are presented in Figs. 5-9. Figure 5 contains the results for activated carbon. As with all of the graphs in Figs. 5-9, the total and elemental mercury curves correspond to the left axis, the temperature curve is scaled by the right axis, and all curves are related by the time at which the data was taken, which is presented on the x-axis.

As shown in Fig. 5, the activated carbon sample removed approximately 90% of the mercury from the flue gas at the 300 °F and 500 °F conditions, but was less effective with increasing temperature. At the highest temperature conditions, carbon in the sample was consumed by oxidation reactions. Hence, the mercury removed as the reactor was subsequently stepped down in temperature was not as great as the earlier condition. Figure 6 illustrates that carbon black, about a third the cost of activated carbon, behaves similar to activated carbon in terms of mercury removal and oxidation enhancement. However, the fraction of mercury removed by carbon black was somewhat less than activated carbon. In addition, the carbon black was more reactive than the activated carbon, such that >90% of the carbon black was

consumed at the higher temperature conditions. Thereafter, the residue had insignificant impact on mercury removal.

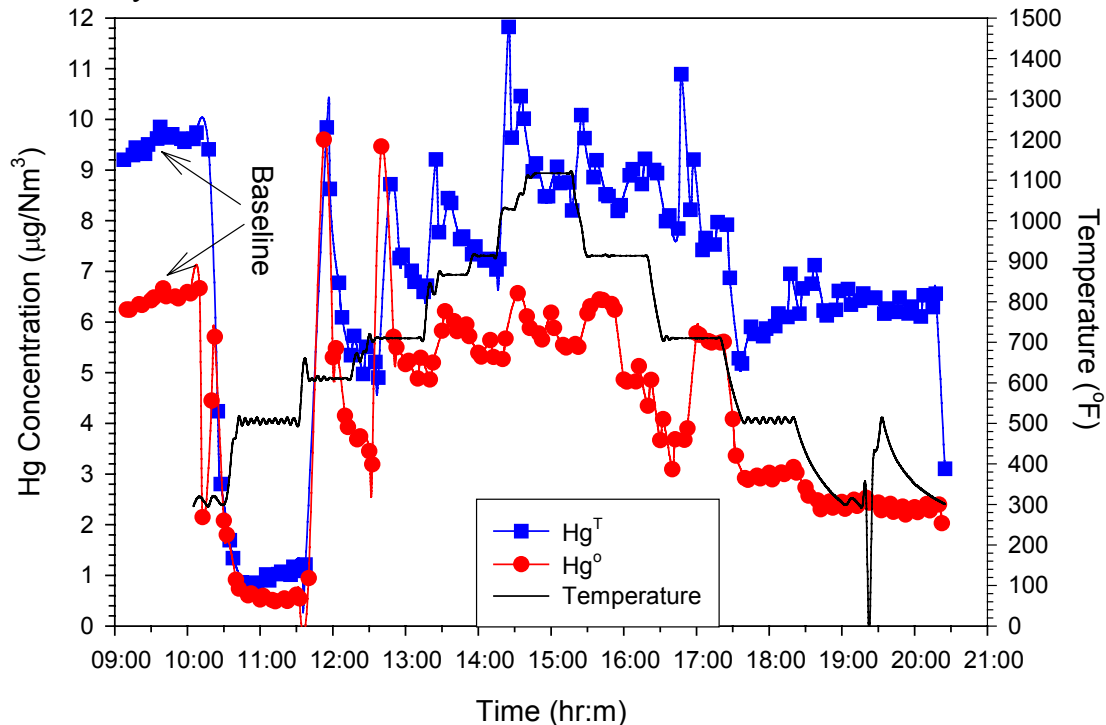


Figure 5. NORIT FGD Activated Carbon.

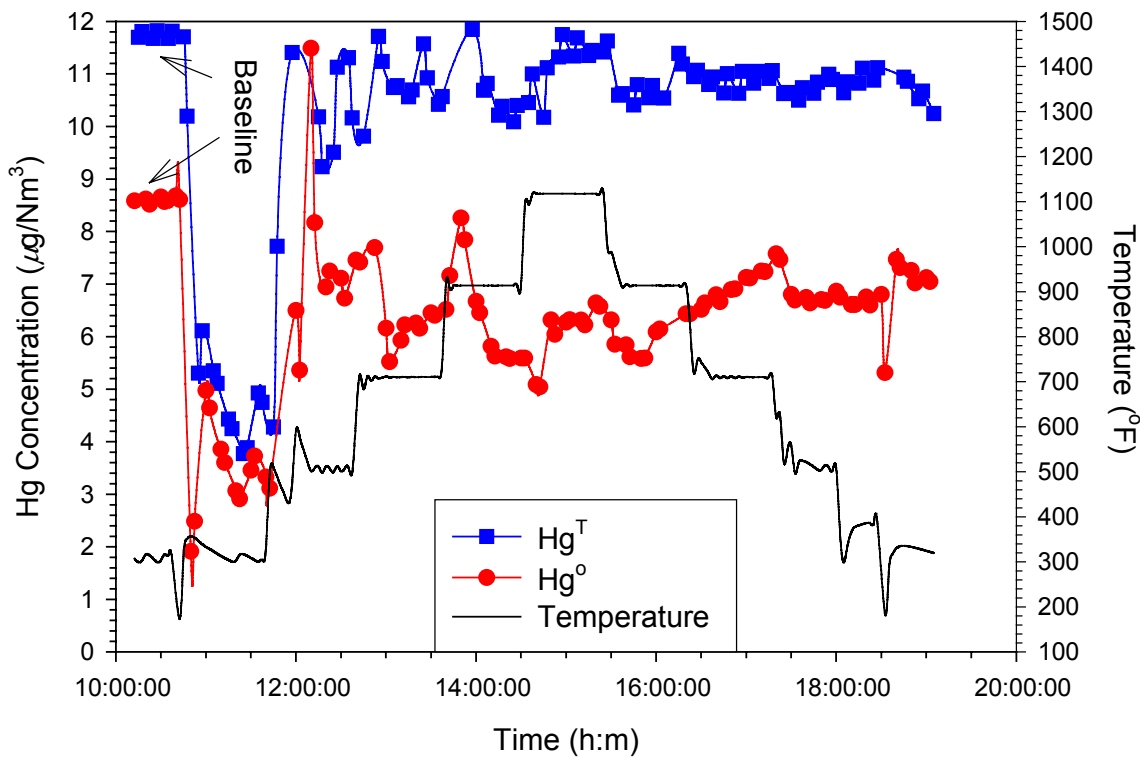


Figure 6. Carbon Black (loose black).

Figure 7 illustrates the lack of effectiveness observed for hydrated lime as a mercury sorbent. Figure 7 also indicates significant low-temperature mercury oxidation enhancement by hydrated lime. The enhanced mercury oxidation is contrary to what has been observed in the pilot tests in the CRF at SRI and in field tests. This is an example of an oxidation mechanism that differs between bench-scale setups and pilot- or full-scale conditions, and is the major reason why the main fundamental and applied research on mercury mitigation must be done on a larger scale, such as in the CRF at SRI. However, as stated earlier, the bench-scale CTF experiments are only being used to compare sorbent removals prior to testing in the pilot-scale facility.

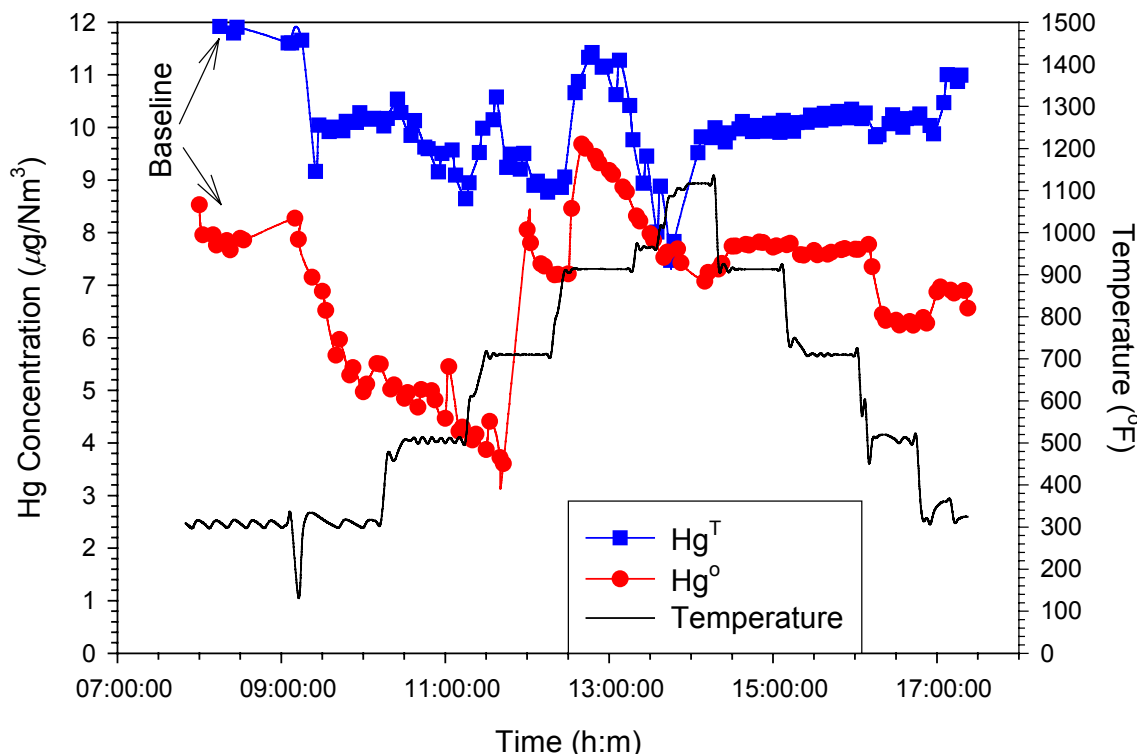


Figure 7. Hydrated Lime.

Figures 8 and 9 illustrate the effectiveness of the manufactured calcium-carbon sorbents on mercury removal. As shown, these trial designer sorbents were much more effective at capturing mercury than hydrated lime alone and were more effective at capturing mercury at 700 °F than either of the carbon-only sorbents. This is consistent with the data observed in both pilot- and field-tests, for mercury removal across baghouses [6-7, 9-12]. These sorbents too however, were subject to carbon-burnout effects on sorbent effectiveness, due to the nature of the bench-scale experimental setup (i.e., long residence times). In order to avoid the carbon burnout effect in future experiments and to avoid residual acid-gas accumulation effects, particularly on activated carbon, future tests will be conducted using a fresh sample for each temperature condition. In addition, some experiments may be performed with 0% excess oxygen. In a full-scale duct, although the oxidizing gases are present, the residence time of the ash and sorbent at the higher temperatures is not long enough for oxidation of all the carbon to occur. Therefore, using 0% oxygen may be a more realistic representation of some full-scale conditions at temperatures where extensive carbon burnout occurs in the micro reactor.

Based on the data taken while the temperature was being ramped up, the sorbent with a higher percentage of carbon (i.e., 10%), shown in Fig. 8, was more effective at removing mercury than the lower-carbon content sorbent (i.e., 4% carbon), shown in Fig. 9.

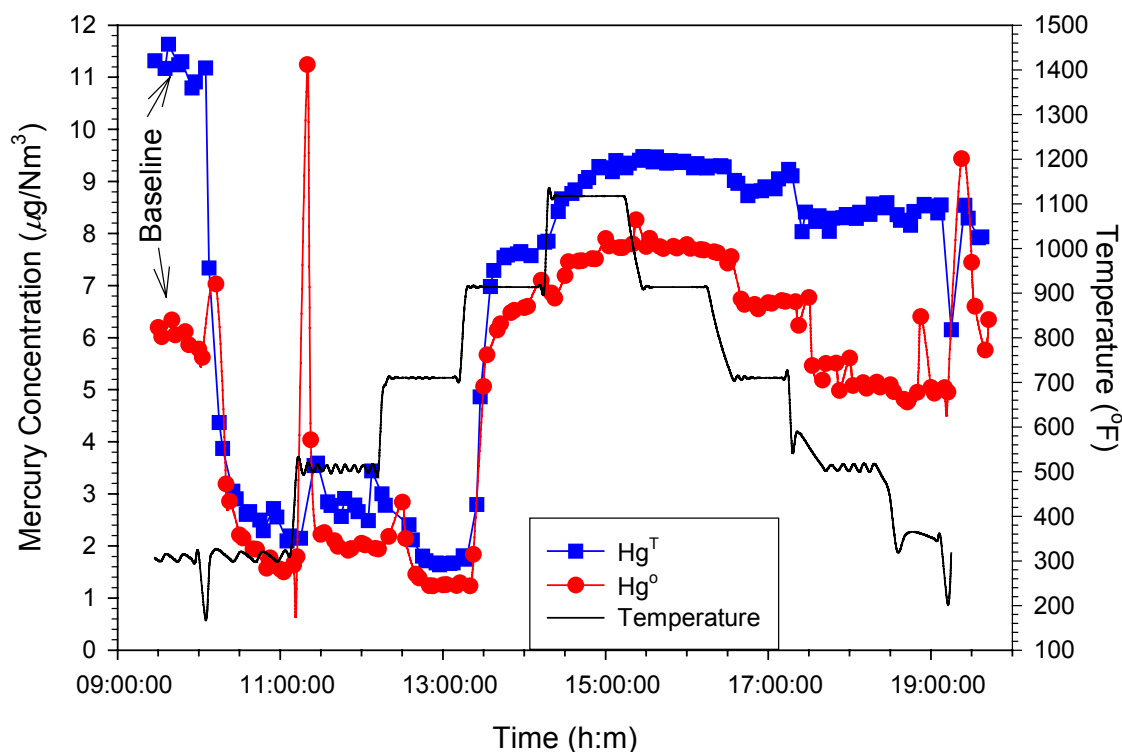


Figure 8. Calcium-based sorbent with 10% carbon bound.

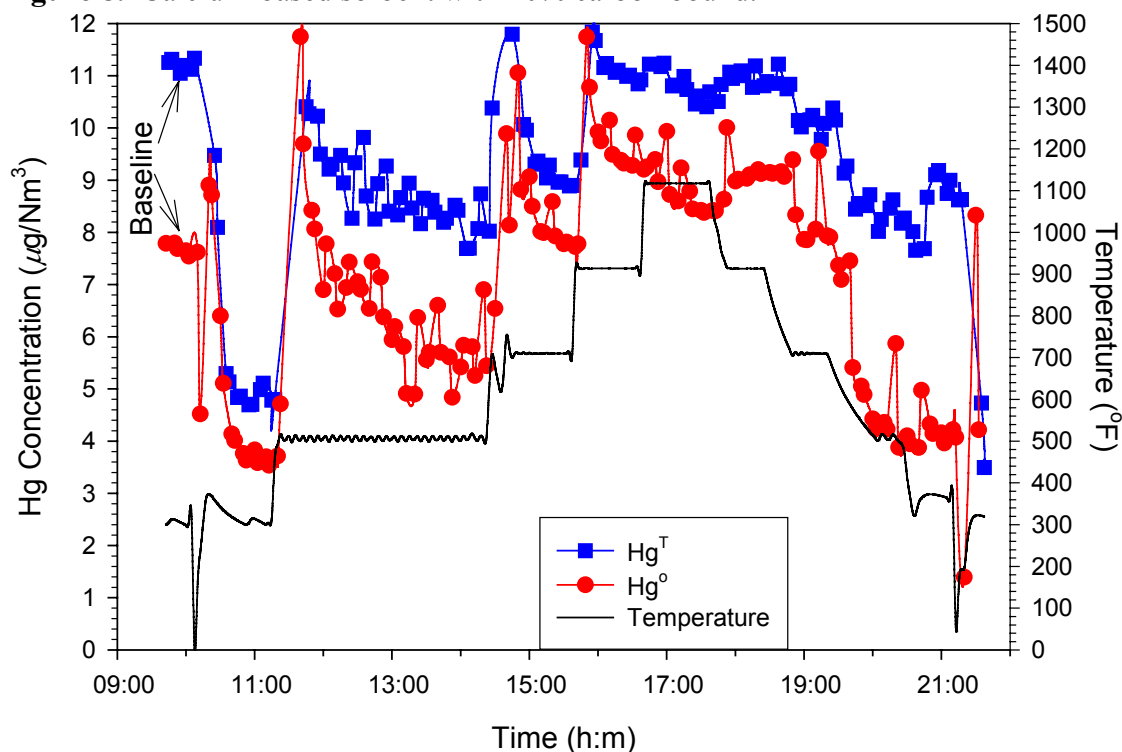


Figure 9. Calcium-based sorbent with 4% carbon bound.

Discussion

Figure 10 contains mercury removal data for each sorbent as a function of temperature, from the data presented in Figs. 5-9. While activated carbon was most effective on a per mass basis at removing mercury at the 300 °F condition, carbon black, and carbon-impregnated calcium designer sorbents were also effective at capturing mercury at the same condition. Hydrated lime alone was not effective at removing mercury.

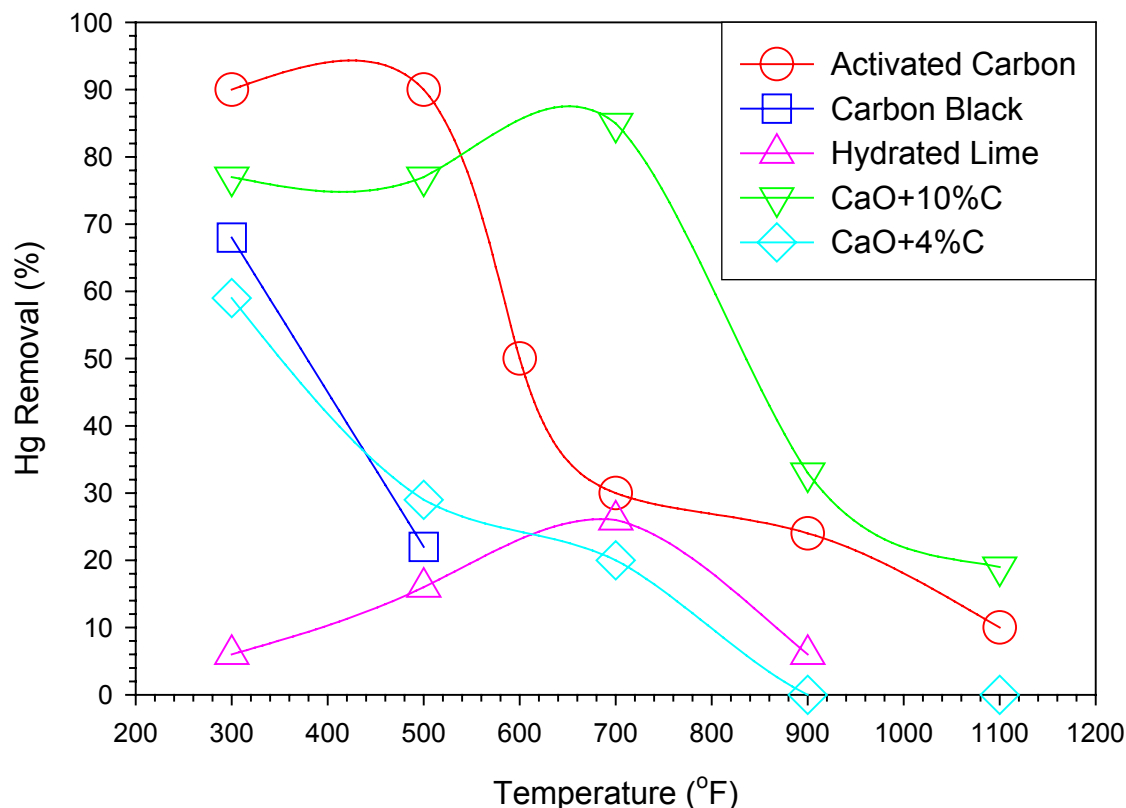


Figure 10. Comparison of sorbents for Hg-mitigation on an equal mass basis.

The higher-carbon-content designer sorbent was more effective at capturing mercury than the lower-carbon-content sorbent. Additional sorbents with higher carbon content will be manufactured to determine the optimum composition for mercury removal across the range of temperature investigated (i.e., 300 to 1100°F). For strictly baghouse applications, the lower temperatures are of most interest. However, for duct injection applications, a sorbent capable of rapidly scavenging mercury from the flue gas along a range of temperatures is desirable. Hence, the carbon-impregnated calcium sorbents appear to have a greater potential for non-baghouse applications than does ordinary activated carbon. This is consistent with previous pilot-scale investigations [6-7, 9-12, 14] and theory [14].

As has been discussed in previous reports and in the background section of this report, there is a synergistic relationship between carbon and calcium with respect to mercury capture. Specifically, carbon has been shown to catalytically enhance reactive capture of both forms of mercury by calcium, either calcium in PRB flyash or calcium-based sorbents. The activated carbon and carbon black data suggest that mercury may adsorb on the carbon at the lower temperatures, then desorb as the temperature increases. The calcium-based sorbents were less

effected by temperature increases until the carbon began to burnout, which is consistent with the understanding of calcium-carbon synergism for the temperature range investigated [14].

Conclusions

Using activated carbon as a standard for comparing other carbon and calcium-based sorbents for mercury removal, the relative effectiveness of several sorbents has been established, based on bench-scale testing in the CTF at Southern Research Institute. Activated carbon was the most effective sorbent at 300 °F and 500 °F, but less effective at higher temperatures. Carbon black was less effective than activated carbon, but followed a similar trend. Calcium-based carbon-impregnated sorbents were similarly effective at 500 °F and 700 °F as they were at 300 °F (particularly the 10%-C impregnated sorbent), which suggests that these designer sorbents are good candidates for duct injection for mercury control, where only an ESP is available for particulate collection.

Future Work

The present and previous results from this project thus far yield information from which the following future tests were conceived.

- 1) Based on the sorbent development investigations discussed in this report, additional tests will be performed to optimize the composition of these designer sorbents using the modified Catalyst Test Facility (CTF) at SRI. Optimized sorbents will then be tested in the CRF to observe the ability of designer sorbents to remove mercury in the disperse phase, through an ESP, and in a baghouse.
- 2) Additional sorbents will be manufactured and tested in the CTF to answer important questions relating to the development of designer sorbents for mercury control. These sorbents include: a) an acid-gas conditioned calcium-based sorbent, and b) additional calcium-carbon sorbents, including those created by the addition of carbon black, to compare to those created by the addition of activated carbon.

References

1. Gale, T. K., “Mercury Control with Calcium-Based Sorbents and Oxidizing Agents” Quarterly Report – DE-PS26-02NT41183 for period Oct. 1st through Dec. 31st, 2002.
2. Senior, C. L., Chen, Z., and Sarofim, A. F., “Mercury Oxidation in Coal-Fired Utility Boilers: Validation of Gas-Phase Kinetic Models”, *A&WMA 95th Annual. Conference.*, Baltimore MD, (2002).
3. Niksa, S., Helble, J. J., Fujiwara, N., “Kinetic Modeling of Homogeneous Mercury Oxidation: the importance of NO and H₂O in predicting oxidation in coal-derived systems”, *Environ. Sci. Technol.*, **35**: 3701-3706 (2001).

4. Niksa, S., Fujiwara, N., Fujita, Y., Tomura, K., Moritomi, H., Tuji, T., and Takasu, S., "A Mechanism for Mercury Oxidation in Coal-Derived Exhausts" *J. A&WMA* **52**: 894-901 (2001).
5. Chen, Z., Senior, C. L., and Sarofim, A. F., "Modeling of Mercury States in Coal-Fired Utility Boilers" *27th Annual Technical Conference on Coal Utilization and Fuel Systems*, Clearwater Florida, March 4-7 (2002).
6. Gale, T. K., "Mercury Control with Calcium-Based Sorbents and Oxidizing Agents" Quarterly Report – DE-PS26-02NT41183 for period Apr. 1st through Jun. 30th, 2003.
7. Gale, T. K. and Merritt, R. L., "Coal Blending, Ash Separation, Ash Re-Injection, Ash Conditioning, and Other Novel Approaches to Enhance Hg Uptake by Ash in Coal-Fired Electric Power Stations" *International Conference on Air Quality IV, Mercury, Trace Elements, and Particulate Matter*, Arlington, VA, September 22-24, 2003.
8. Niksa, S. and Fujiwara, N., "Predicting Mercury Speciation in Coal-Derived Flue Gases", *EPRI-DOE-EPA-A&WMA Combined Utility Air Pollution Control Symposium: The MEGA Symposium*, May (2003).
9. Gale, T. K., "Mercury Control with Calcium-Based Sorbents and Oxidizing Agents" Quarterly Report – DE-PS26-02NT41183 for period Jan. 1st through Mar. 31st, 2003.
10. Gale, T. K., "Mercury Control with Calcium-Based Sorbents and Oxidizing Agents" DOE Mercury Control Technology R&D Program Review Meeting, Aug. 12-13, 2003.
11. Gale, T. K., "Mercury Control with Calcium-Based Sorbents and Oxidizing Agents" Quarterly Report – DE-PS26-02NT41183 for period Jul. 1st through Sep. 30th, 2003.
12. Gale, T. K., Merritt, R. L., Cushing, K. M., and Offen, G. R., "Mercury Speciation as a Function of Flue Gas Chlorine Content and Composition in a 1 MW Semi-Industrial Scale Coal-Fired Facility", *EPRI-DOE-EPA-A&WMA Combined Utility Air Pollution Control Symposium: The MEGA Symposium*, May (2003).
13. Hurt, R. H. and Gibbins, J. R., "Residual Carbon from Pulverized Coal Fired Boilers: 1. Size Distribution and Combustion Reactivity", *Fuel* **74**(4): 471-480 (1995).
14. Gale, T.K., "The Effect of Coal Type and Burnout on Mercury Speciation Across a Baghouse", *Annual ACERC Conference*, Provo, Utah, February 12-13, 2004.